Performance of Compact Fluorescent Lamps at Different Ambient Temperatures

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Introduction

Compact fluorescent lamps are used to replace incandescent lamps to aid in energy conservation in commercial and domestic lighting applications. In particular, they offer the benefits of much longer life and lower operating costs in a reasonably similar package.[2] Some of the performance characteristics familiar to residential users may differ for the newer lamp technology. Such characteristics include response to ambient thermal conditions, sensitivity to lamp position, flicker, harmonics, etc. Of particular concern is the response to ambient thermal conditions, since lamps are used in unconditioned spaces, such as garages, basements, barns, and similar spaces where they may be subjected to extremes in temperature, both hot and cold. While it is well known that fluorescent lamp performance is determined by the cold spot on the lamp and can be affected by the ambient temperature in the room,[5] the extent to which these findings, particularly for extreme in temperatures, apply to compact fluorescent lamp applications is not well understood.

In conjunction with the Institute for Research in Construction (IRC) at the National Research Council, Canada (NRCC), the Lighting Group at the National Institute of Standards and Technology (NIST) conducted an experimental evaluation of twelve sets of different types of compact fluorescent lamps at six different ambient temperature conditions. An additional set of incandescent lamps was also evaluated for comparison. A total of three lamps were tested for each of the thirteen lamp types, both compact fluorescent and incandescent.

Procedure

Using a large environmental chamber, NIST performed a number of tests on the compact fluorescent samples at six different ambient temperatures. The intent of the research project was to investigate the sensitivity of different compact fluorescent lamp types to various ambient temperatures, rather than to characterize the performance of specific lamps. Thus, while no attempt was made to select identical lamp types from various manufacturers, test lamp samples were selected to cover a range of lamp/ballast types to enable some assessment of the effects of lamp type, ballast type, and the presence of an enclosure on temperature sensitivity. The compact fluorescent lamps were provided by NRCC/IRC and had been burned-in for approximately 100 hrs prior to the NIST tests. Details of the experimental procedure are discussed in a companion report by Collins, Treado, and Ouellette.[3] Each set of tests involved measurements of a set of three identical compact fluorescent lamps mounted base-up on a metal frame suspended in the environmental chamber. Lamps were mounted on each of three arms radiating from a central area. The entire array was suspended from an overhead arm. Each lamp was approximately 60 cm from its neighbors and suspended about 1 m above a diffuse white plate and photocell used to monitor light output during the testing.

Lamps 1 – 12 consisted of sets of three identical compact fluorescent lamps, while lamp 13 was a set of three 60-W incandescent lamps used as the reference lamp for comparison. The incandescent lamps, which are known not to be sensitive to temperature, were included for reference measurements and to provide a means for checking instrumentation stability. All the compact fluorescent samples were designed to operate at 120 V AC. Power ratings ranged from 13 to 28 W. The lamp sets are described as follows:

Lamp 1: T4 13-W twin tube with plug in magnetic ballast

Lamp 2: 16-W globe with integral ballast and screw in base

Lamp 3: T4 20-W quad tube with integral ballast and screw in base

Lamp 4: T4 18-W globe with integral ballast and screw in base

Lamp 5: T4 13-W quad tube with integral ballast and screw in base

Lamp 6: Lamp 5 with a globe

Lamp 7: T4 26-W quad tube with external ballast and mounting hardware

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Lamp 8: T5 24-W twin tube with external ballast and mounting hardware

Lamp 9: T5 28-W quad tube with external ballast and mounting hardware

Lamp 10: T4 13-W twin tube with separate ballast adapter and screw base

Lamp 11: 13-W twin tube with integral ballast and screw in base

Lamp 12: Low voltage (12 V) 13-W twin tube with separate ballast and mounting hardware

Lamp 13: 60-W frosted incandescent aquarium lamp

Lamps 3 and 4 contained integral electronic ballasts, while all the other lamps had magnetic-core ballasts, either separate or integral. Lamps 7 and 8 included high-power-factor-correction circuits, while lamp 8 also contained a constant illumination circuit intended to provide constant illumination throughout a range of voltages. Since there were three samples for each lamp type, individual lamps in a set were designated as A, B, and C.

Lamp performance was evaluated for a total of six temperatures ranging from 45 °C to 18 °C, including the burn-in temperature of 25 °C. The temperatures included 45, 25, 10, 0, −9, and −18 °C (113, 77, 50, 32, 16, and 0 °F). Temperature in the environmental chamber was maintained to within ±1.5 °C. At each temperature condition, the following parameters were measured:

- lamp ignition time or failure
- time to luminous equilibrium and electrical stabilization
- relative luminous flux density at a point 1 m below the central point
- electrical power in watts and volt amps
- minimum lamp wall or globe temperature as applicable
- relative luminous efficacy
- total harmonic distortion
- power factor

In addition lamp performance was assessed for a simulated frost condition in which lamps were misted at −4 °C and time to ignition determined.

The luminous output of the lamps was measured in two ways, by measuring illuminance beneath the lamp array, and by measuring the luminance of a white tile also located beneath the lamps. Two measurement methods were used to control for possible changes in the responsiveness of the illuminance photocell due to ambient temperature. The silicon photocell was mounted 1 m below the center of the lamps and attached to a datalogger that recorded light output continuously, allowing for a determination of luminous equilibrium. The silicon cell was a photovoltaic cell with a V_λ filter, and a cosine diffuser connected to an amplifier. A Minolta luminance meter was used to measure luminance from the white plate located at the center of the three lamps also located 1 m below the mounting center for the three lamps after equilibrium, allowing the determination of lamp light output (relative to the same lamps at other temperatures). This meter was positioned about 2 m from the plate at about 30° from normal for the measurements, and was removed from the chamber between measurements to minimize all thermal effects.

It should be noted that since the photometric distribution of the various lamp types differed, lamp light output cannot be compared across lamp types. Such a comparison would have required the measurement of lamp total luminous flux (such as would be obtained in an integrating sphere or distribution photometer). However, the intent of the project was to investigate the effect of ambient temperature on lamp performance, not to compare various lamps, a task for which relative light output as measured is well suited. Relative light output was measured once the lamps had been determined to be at luminous and electrical equilibrium. The temperature of each of the three lamps was measured by means of a thermocouple attached to the bottom tip of each lamp (or globe where applicable) and connected to the datalogger as well. A fourth thermocouple monitored ambient temperature in the environmental chamber. The four temperature and luminous photocell outputs were recorded by the datalogger every 5 min. All photocells and thermocouples were located in the environmental chamber throughout the measurement period. The photocell manufacturer reported minimal sensitivity to temperature extremes for the visible range at the temperatures tested.

A power profiler recorded electrical information including voltage, current, power, total harmonic distortion, power factor, and changes in electrical characteristics of the lighting systems over time. All electrical recording equipment was located in a room outside the environmental chamber to maintain temperature stability. (Luminance readings were taken rapidly once the lamps had reached equilibrium using the luminance meter which was normally kept outside the chamber.) Power to the lamps was provided by means of a regulated power supply which maintained an input voltage at 122 ± 1 V and THD ± 3 percent. The low voltage system was powered by a 20-Vdc power supply operating at 12 ± 0.1 V.

The three lamps were mounted on the test apparatus prior to beginning each test session and setting the temperature in the environmental chamber. After the environmental chamber (and lamps) had stabilized at the pre-determined test temperature, the lamps were ignited. Time to ignition was measured in seconds. Lamp wall and ambient temperature were measured and recorded every 5 min, while the electrical parameters were continuously monitored and recorded. In addition, a record of lamp system input electrical conditions was taken at the beginning and end of a test session for each lamp type. Lamp relative light output (luminance) was measured at the end of each test session using the luminance meter. Throughout each test session, lamp light output was monitored using a silicon photocell. (This output is referred to subsequently as photocell output.) Lamps were considered to be at equilibrium when three light output (photocell) readings taken consecutively within 15 min did not differ by more than ±1 percent. Data are reported for all three lamps combined except where failure of one or more lamps occurred.

Experimental results

Lamp performance was measured for ambient temperatures in the following order: 25, 45, 10, 0, −9, −18, −4 with mist, and 25 °C again. The baseline condition, 25 °C, was repeated at the end to determine changes in lamp performance or the extent of lamp degradation as a function of thermal stress and operation. The results for the repeated condition are designated as 25R. In addition, where one of the lamps failed during the course of the data collection, measures were repeated at 25 °C with only two lamps (noted as 25-2 in the table).

Table 1 summarizes the results for the time to lamp ignition or failure (when appropriate). Lamps were considered to have failed if they did not ignite within 5 min of being started. Since three lamps were assessed, there were three possibilities for failure. No lamps failed for temperatures greater than 0 °C. At 0 °C, however, there were two failures. Lamp 7B broke when tapped gently during the mounting procedure, and lamp 8B refused to start at this temperature. At −9 °C lamp 5C refused to start, as did all three lamps in group 8. At −18 °C, lamp 5C ignited only after the wires in its socket were tightened. Lamp 12 refused to start at temperatures below 0 °C, with one lamp failing at the initial 25 °C condition. This lamp failed because an uninsulated diode was shorted out after touching the "live" ballast housing. As a result, much less complete data were obtained for lamp 12. Lamp 5A (and consequently 6A) began to experience ignition problems at 10 °C. It required adjusting the socket and twisting the lamp to get it to ignite. It finally failed completely at −18 °C. Most lamps evidenced problems at the coldest conditions (−18 °C or 0 °F) with only lamps 3, 4, 9, and 13 starting rapidly.

Table 2 summarizes lamp performance data obtained once the lamps had achieved thermal and luminous equilibrium. This table presents data on time to ignition (in seconds), time to luminous equilibrium (in minutes), temperature at the bottom tip of each lamp, lamp luminance in cd/m^2, lamp light output (in nominal volts), luminous efficacy (in cd/m^2/W), relative luminous efficacy (relative to performance at 25 °C, lamp input power in watts and volt amps, power factor, total harmonic distortion (for voltage and current), input voltage, and input current for each test. (Blanks in the table represent conditions for which no data were obtained.)

The next set of data discussed pertain to the time to luminous equilibrium, as well as for total light output over time for all lamps except lamp 12. Luminous equilibrium was defined as three consecutive readings that did not deviate by more than 1 percent from the immediately preceding measurement. Data for determining luminous equilibrium were typically collected for 60 − 90 min in 5 min increments following ignition. Relative light output was determined by averaging the last three photocell readings, and then dividing each prior reading by this mean.

For lamp 1, light output was almost identical for 25 and 45 °C, with time to equilibrium achieved rapidly and maintained for 1 to 1.5 hrs. At 10 °C light output reached the same levels but then declined to a new, much lower equilibrium level after 60 − 70 min. At even cooler temperatures, light output peaked and then declined markedly with equilibrium occurring after about 60 − 70 min. Relative light output declined steadily over time at the cooler temperatures to a value of less than half that at 25 °C. Unlike lamp 1, the data for lamp 2 showed much less variation over time as a function of temperature, although the data showed a peculiar initial decline in output for the two higher temperatures followed by a return to approximately the same light output obtained for the other temperatures. Total light output was much higher than for lamp 1 and was much less affected by changes in room temperature; perhaps because of the presence of a globe that insulated it. The time to luminous equilibrium and the relative light output for lamp 3 was about the same regardless of temperature. The overall light output was highly temperature dependent, dropping markedly for temperatures below 0 °C. Lamp 3 did not really reach a stable equilibrium at either −9 or −18 °C during the 90 min of operation.

Lamp 4 demonstrated much less decline in light output than lamp 3 as a function of time and ambient temperature. For most of the ambient temperatures, light output was relatively constant after about 30 to 60 min. At −18 °C, however, there was a noticeable decline in light output after about an hour at that

Table 1—Time to ignition in seconds for each lamp set at each ambient temperature

Lamp number	25 °C	45 °C	10 °C	0 °C	−4 °C	−9 °C	−18 °C	25R
No 1 13 W TT	3	2.5	3.5	3	2	3	25 C 13 A&B	3
No 2 16 W Globe	2.5	2	3	5	3	6	11	3
No 3 20 W QT	1	1.5	1.5	2	1	2	3	2
No 4 18 W Globe	2	1.5	3	5	failed	5	5	3.5
No 5 13 W QT	5	5	4.5	6.5 A slow	failed	25[2]	205[2]	7
No 6 13 W Globe	6	5	5	5	5	25	451	6
No 7 26 W QT	2.5	3	4	4[1]	3	5	411	3
No 8 24 W TT	2.5	0.5	0.5	1.5	failed	glowed	failed	0.5
No 9 28 W QT	2.5	1.5	4.5	3.5	2	4	4	3.5
No 10 13 W QT	4	4	4.5	3.5	5	20	130	4
No 11 13 W TT	5.5	4	3.5	5	5	40	360 170 C	5
No 12 13 W TT LoV		5	5	5		failed	failed	5
No 13 60 W Incandescent	0.5	0.5	0.5	0.5		0.5	0.5	0.5

[1] *7C just broke before 0 °C condition due to its increased fragility in the cold*
[2] *A failed*

temperature. The data suggests that light output for lamp 4 reached an early peak, dropped back and then increased for the coldest and warmest temperatures. Light output for this set of lamps [which also had a surrounding globe] appeared relatively unaffected by temperature.

On the other hand, luminous output for lamp 5 was noticeably reduced at the two coldest temperatures, with an initially higher output followed by a decline after about 20 to 30 minutes at −9 and −18 °C. One of the lamps (C) in set 5 actually failed at these temperatures. At temperatures above −9 °C, light output from these lamps tended to reach an equilibrium relatively rapidly and maintain it, however. When these same lamps were placed in an enclosure (for the lamp 6 configuration), the surrounding globe apparently insulated them from the effects of the colder ambient temperatures since light output for lamp 6 was higher at both −9 and −18 °C and was more stable over time, than for lamp 5.

Lamp 7 tended to reach equilibrium early, with relatively little fluctuation in output over time. There was a marked decline in light output as temperature deviated from 25 °C, however. (It should be pointed out that the data at the lowest temperatures represent the output of only two lamps since one was broken

Table 2—Summary of Test Results for Each Lamp Set as a Function of Ambient Temperature

Lamp 1

(°C) (Ambient temperature)	45	25	25 R	10	0	−9	−18
Time to ignite (s)	2.5	3.0	3.0	3.5	3.0	3.0	25.0
Time to equil (min)	44.0	35.0	39.0	74.0	100.0	75.0	84.0
Temp lamp A (°C)	51.1	36.9	39.7	22.5	13.4	1.1	−16.8
Temp lamp B	54.3	40.0	39.0	23.1	18.2	2.1	−7.4
Temp lamp C	48.7	37.7	35.9	23.2	13.5	0.3	−9.2
Lamp luminances (cd/m^2)	18.0	18.0	18.1	9.9	4.5	2.1	0.9
Voltage (V)	0.25	0.25	0.25	0.16	0.07	0.04	0.01
Power (W)	56.4	54.1	54.3	53.9	52.6	49.9	48.7
LumEff (cd/m^2/W)	0.09	0.10	0.10	0.05	0.02	0.01	0.01
Relative LumEff	0.96	1.00	1.00	0.55	0.25	0.13	0.06
Power (V-A)	113.7	106.8	107.0	114.0	118.2	115.2	126.6
Power factor	0.50	0.51	0.51	0.47	0.45	0.43	0.38
THD voltage	3.7	3.7	3.7	3.7	3.7	3.7	3.5
THD current	11.7	12.7	12.5	11.3	11.0	11.3	14.1
Input voltage	121.4	121.3	121.6	121.3	121.5	121.6	121.5
Current	930.0	865.0	880.0	939.0	972.0	948.0	1042.0

Lamp 2

(°C) (Ambient temperature)	45	25	25 R	10	0	−9	−18
Time to ignite (s)	2.0	2.5	3.0	3.0	5.0	6.0	11.0
Time to equil (min)	84.0	110.0	75.0	55.0	72.0	70.0	63.0
Temp lamp A (°C)	61.8	44.6	44.2	30.0	21.6	14.4	2.7
Temp lamp B	49.0	44.1	42.4	28.6	21.5	10.8	2.3
Temp lamp C	62.4	43.6	43.5	31.2	20.1	12.2	5.1
Lamp luminances (cd/m^2)	33.9	36.3	34.5	34.3	33.9	29.5	31.9
Lamp Output (V)	0.47	0.49	0.49	0.47	0.46	0.43	0.43
Power (W)	52.0	52.1	51.9	52.2	51.8	50.9	51.4
LumEff (cd/m^2/W)	0.19	0.20	0.19	0.19	0.19	0.17	0.18
Relative LumEff	0.94	1.00	0.95	0.94	0.94	0.83	0.89
Power (V-A)	94.5	95.1	95.2	98.2	99.5	94.8	92.2
Power factor	0.55	0.54	0.54	0.53	0.52	0.54	0.53
THD voltage	3.8		3.8	3.5	3.7	3.7	3.8
THD current	11.2		11.0	10.9	10.2	11.3	11.0
Input voltage	121.5	121.7	121.8	121.7	121.9	121.9	121.7
Current	767.0	781.4	782.0	798.0	816.0	778.0	791.0

Lamp 3

(°C) (Ambient temperature)	45	25	25 R	10	0	−9	−18
Time to ignite (s)	1.5	0.5	2.0	1.5	2.0	2.0	3.0
Time to equil (min)	82.0	49.0	40.0	76.0	89.0	60.0	89.0
Temp lamp A (°C)	45.2	54.2	52.8	39.2	24.4	18.4	1.7
Temp lamp B	45.6	58.4	52.3	38.0	27.0	20.7	13.8
Temp lamp C	46.3	46.2	51.6	40.6	37.0	16.3	8.8
Lamp luminances (cd/m^2)	28.2	28.4	32.1	32.6	26.0	16.0	10.5
Lamp output (V)	0.40	0.41	0.44	0.47	0.37	0.24	0.15
Power (W)	48.1	53.3	55.4	56.9	55.9	51.9	50.6
LumEff (cd/m^2/W)	0.17	0.16	0.17	0.17	0.14	0.09	0.06
Relative LumEff	1.10	1.00	1.09	1.08	0.88	0.58	0.39
Power (V-A)	70.4	99.1	80.5	82.9	81.5	76.2	74.2
Power factor	0.68	0.68	0.69	0.69	0.69	0.68	0.68
THD voltage	4.6		4.4	4.4	4.5	4.5	4.5
THD current	102.2		100.9	100.8	101.2	102.1	102.6
Input voltage	122.4	122.9	122.9	122.6	122.4	122.5	122.5
Current	402.0	633.0	655.0	676.0	666.0	622.0	606.0

during the setup for 0 °C). Nonetheless, light output was noticeably diminished for these two lamps at the coldest temperatures with reduced output apparent even at 10 °C.

Lamp 8 also showed marked effects of temperature with a noticeable decline in light output at 0 °C and complete failure at temperatures below 0 °C. Unlike most of the other lamps, light output for these lamps was actually lower at 25 °C than at 10 or 45 °C. Light output increased at 10 °C for the first minutes, before returning to values similar to those at 45 °C. This lamp contained a constant illumination circuit which

Table 2—Continued

(°C) (Ambient temperature)	Lamp 4 45	25	25 R	10	0	−9	−18
Time to ignite (s)	1.5	2.0	3.5	3.0	5.0	5.0	5.0
Time to equil (min)	94.0	165.0	90.0	85.0	79.0	95.0	109.0
Temp lamp A (°C)	59.5	42.8	27.8	28.4	17.9	10.4	0.0
Temp lamp B	59.3	41.5	44.1	31.8	20.6	11.0	3.4
Temp lamp C	61.6	45.3	43.8	31.1	21.4	9.9	
Lamp luminances (cd/m^2)	29.6	29.5	30.5	29.8	29.8	27.9	24.9
Lamp output (V)	0.42	0.43	0.42	0.43	0.43	0.40	0.35
LumEff (cd/m^2/W)	0.15	0.15	0.16	0.15	0.15	0.14	0.13
Relative LumEff	1.01	1.00	1.05	1.03	1.04	0.97	0.89
Power (W)	58.15	58.3	57.28	57.3	56.71	56.64	55.56
Power (V·A)	107.3	107.6	105.8	106.2	105.3	105.0	103.0
Power factor	0.54	0.55	0.54	0.54	0.54	0.54	0.54
THD voltage	4.4	4.5	4.4	4.5	4.4	4.4	4.4
THD current	138.1	138.5	138.6	139.4	139.5	139.2	139.2
Input voltage	122.4	122.5	122.6	122.6	122.6	122.5	122.7
Current	515.0	513.0	863.0	866.0	859.0	857.0	839.0

Lamp 5 (experienced problems with Lamp C)

(°C) Ambient Temperature	45	25	25 R	10	0	−9	5B&C −18	25 − 2
Time to ignite (sec)	5.0	5.0	7.0	4.5	6.5	25.0	205.0	5.0
Time to equil (min)	24.0	22.0	14.0	49.0	74.0	78.0	76.0	14.0
Temp lamp A (°C)	57.8	53.9	48.7	41.0	30.5	15.7		24.8
Temp lamp B	65.0	54.6	52.2	41.3	35.8	18.7	9.9	52.2
Temp lamp C	64.9	35.3	49.3	34.5	29.6	13.3	4.1	49.1
Lamp luminances (cd/m^2)	15.8	16.9	19.3	18.9	15.3	6.8	2.1	14.1
Voltage (V)	0.23	0.23	0.26	0.28	0.22	0.10	0.03	0.19
Power (W)	48.5	47.8	47.9	46.1	46.5	45.2	29.0	32.6
LumEff (cd/m^2/W)	0.10	0.10	0.12	0.12	0.10	0.04	0.02	0.13
Relative LumEff	0.81	0.88	1.00	1.02	0.82	0.37	0.18	1.08
Power (V·A)	91.4	85.8	85.14	80.18	84.14	90.36	59.24	58.7
Power factor	0.5	0.56	0.56	0.58	0.55	0.50	0.49	0.56
THD voltage	3.7		3.8	3.8	3.8	3.8	4.0	3.9
THD current	8.2		10.1	11.7	10.7	8.9	9.4	10.2
Input voltage	121.8	121.8	121.8	121.8	122.0	121.7	122.2	122.1
Current	747.0	704.0	699.0	659.0	699.0	743.0	485.0	481.0

Lamp 6 (experienced problems with Lamp C)

(°C) (Ambient temperature)	45	25	25 R	10	0	−9	−18
Time to ignite (s)	5.0	6.0	6.0	5.0	5.0	25.0	451.0
Time to equil (min)	29.0	35.0	25.0	23.0	25.0	59.0	76.0
Temp lamp A (°C)	48.8	31.4	30.7	17.3	7.9	−1.3	−17.8
Temp lamp B	47.3	30.5	31.1	17.8	7.8	−0.7	−10.3
Temp lamp C	49.3	30.5	30.4	17.3	8.0	−1.4	−11.2
Lamp luminances (cd/m^2)	13.3	17.1	16.5	14.8	18.5	17.2	6.6
Lamp Output (V)	0.19	0.22	0.22	0.26	0.26	0.24	0.09
Power (W)	48.04	48.40	48.07	47.44	46.84	46.19	30.75
LumEff (cd/m^2/W)	0.08	0.10	0.10	0.09	0.12	0.11	0.06
Relative LumEff	0.79	1.00	0.97	0.88	1.12	1.06	0.61
Power (V·A)	96.7	84.83	90.74	84.42	81.58	81.6	58.66
Power factor	0.5	0.54	0.53	0.56	0.57	0.57	0.52
THD voltage	3.8		3.8	3.8	3.8	3.8	3.9
THD current	7.1		8.5	10.1	11.2	11.6	9.3
Input voltage	121.6	121.9	121.7	121.8	122.0	122.2	122.1
Current	785.0	742.0	745.0	694.0	669.0	668.0	481.0

appears to have been effective at the higher temperatures. Some rather strange temperature effects occurred for lamp 9 with a marked decline in output for the two coldest temperatures and a late drop in output at the warmest temperature (45 °C) about 90 min into the test period. This sudden drop in the last four data points appears to be an unanticipated, delayed response to thermal stress. Colder temperatures markedly reduced light output for this set of lamps with an output at −18 °C of only about 20 percent of that at 10 °C, for example.

Light output for lamp 10 was also reduced at the

Table 2—Continued

(°C) (Ambient temperature)	Lamp 7 45	25	25 R	10	0	−9	−18	25 − 2
Time to ignite (sec)	3.0	2.5		4.0	4.0	5.0	411.0	3.0
Time to equil (min)	80.0	70.0		128.0	79.0	142.0	82.0	53.0
Temp lamp A (°C)	59.1	52.6		35.2	31.9	3.9	10.7	45.6
Temp lamp B	62.4	54.8		39.1	32.4	23.1	−3.1	54.8
Temp lamp C	62.5	42.6		36.1	28.6	Broken		24.6
Lamp luminances (cd/m^2)	27.1	36.0		28.6	14.7	5.2	2.6	20.5
Lamp Output (V)	0.37	0.49		0.42	0.22	0.08	0.04	0.28
Power (W)	93.46	93.39		92.26	60.95	58.01	55.41	61.95
LumEff (cd/m^2/W)	0.08	0.11		0.09	0.07	0.03	0.01	0.10
Relative LumEff	0.75	1.00		0.80	0.63	0.23	0.12	0.86
Power (V·A)	165.6	171.4		168.3	91.97	90.9	89.82	92.89
Power factor	0.56	0.54		0.55	0.66	0.64	0.62	0.67
THD voltage	8.3	8.8		8.7	6.3	6.3	6.3	6.3
THD current	138.8	153.4		154.4	113.6	115.2	119.5	111.9
Input voltage	122.1	122.0		122.5	122.5	122.5	122.5	122.87
Current	798.0	771.0		755.0	751.0	742.0	733.0	756.0

°C (Ambient temperature)	Lamp 8 45	25	25 R	10	0	−9	−18	25 − 2
Time to ignite (s)	0.5	2.5	0.5	0.5	1.5	44 min		0.5
Time to equil (min)	35.0	50.0	31.0	79.0	59.0			54.0
Temp lamp A (°C)	52.0	42.1	39.1	24.6	16.2	−8.5		39.2
Temp lamp B	54.1	43.3	41.9	29.0		−8.5		23.9
Temp lamp C	52.1	41.8	39.6	25.0	16.2	−8.6		39.1
Lamp luminances (cd/m^2)	16.5	17.7	19.4	14.7	3.7	0.0		12.8
Lamp Output (V)	0.23	0.24	0.27	0.22	0.06	0.01		0.17
Power (W)	100.8	104.5	106.6	104.3	64.9	29.1		72.2
LumEff (cd/m^2/W)	0.05	0.05	0.05	0.04	0.02	0.00		0.05
Relative LumEff	0.96	1.00	1.07	0.83	0.34	0.00		1.04
Power (V·A)	103.5	107.3	109.0	106.7	66.6	111.8		74.16
Power factor	0.98	0.97	0.98	0.98	0.97	0.26		0.97
THD voltage	4.0	4.0	4.0	4.0		3.8		4.0
THD current	10.9	11.6	11.9	13.0		24.5		12.7
Input voltage	122.0	122.0	122.0	121.9	121.8	121.7		122.2
Current	845.0	869.0	893.0	875.0	547.0	919.0		607.0

(°C) (Ambient temperature)	Lamp 9 45	25	25 R	10	0	−9	−18
Time to ignite (s)	1.5	2.5	3.5	4.5	3.5	4.0	4.0
Time to equil (min)	56.0	62.0	54.0	65.0	49.0	89.0	89.0
Temp lamp A (°C)	63.0	58.1	50.8	32.3	24.8	20.6	2.0
Temp lamp B	66.4	70.4	50.9	42.1	29.6	21.2	9.2
Temp lamp C	67.7	51.6	49.2	35.9	19.6	14.5	5.2
Lamp luminances (cd/m^2)	30.8	33.6	35.6	36.7	26.8	14.1	7.3
Voltage (V)	0.42	0.46	0.49	0.53	0.39	0.20	0.10
Power (W)	103.7	105.4	106.9	106.5	105.6	102.8	0.9
LumEff (cd/m^2/W)	0.09	0.09	0.10	0.10	0.07	0.04	0.02
Relative LumEff	0.93	1.00	1.05	1.08	0.80	0.43	0.23
Power (V·A)	240.2	225.6	225.9	217.6	225.7	237.1	240.4
Power factor	0.43	0.47	0.47	0.49	0.47	0.43	0.42
THD voltage	3.2	3.3	3.3	3.3	3.2	3.1	
THD current	8.4	8.4	9.2	8.1	7.1	6.7	
Input voltage	119.9	120.0	120.1	120.1	119.9	119.9	119.7
Current	2010.0	1872.0	1880.0	1812.0	1882.0	1972.0	2008.0

lowest two temperatures, with output at −9 °C initially being the same as that at 45 °C, but then immediately falling off to about 60 percent of the output, and that at −18 °C steadily declining after the first five min and reaching a final value of about 15 percent of that at the baseline condition. Output at 45 °C was actually slightly below that at 0 °C, although there was greater variability in the time to equilibrium for the latter. Relative light output was reasonably stable after 5 to 15 min of operation for temperatures above −9 °C, however. As with lamp 9, lamp 11 also displayed a peculiar drop in light output at 45 °C at

Table 2—Continued

Lamp 10							
(°C) (Ambient temperature)	45	25	25 R	10	0	−9	−18
Time to ignite (s)	4.0	4.0	4.0	4.5	3.5	20.0	130.0
Time to equil (min)	29.0	30.0	29.0	44.0	59.0	85.0	73.0
Temp lamp A (°C)	65.9	57.6	52.9	39.0	31.2	15.5	4.1
Temp lamp B	50.5	56.2	53.1	41.6	29.8	23.5	6.9
Temp lamp C	74.0	53.9	50.3	38.9	33.9	19.4	12.3
Lamp luminances (cd/m^2)	15.9	17.8	18.9	19.5	16.9	10.1	3.5
Lamp Output (V)	0.22	0.25	0.27	0.29	0.25	0.15	0.06
Power (W)	60.39	59.17	57.89	55.95	55.68	56.83	54.81
LumEff (cd/m^2/W)	0.08	0.09	0.10	0.10	0.09	0.05	0.02
Relative LumEff	0.87	1.00	1.08	1.16	1.00	0.59	0.21
Power (V·A)	113.05	121.10	104.40	97.71	98.76	108.0	110.1
Power factor	0.55	0.49	0.55	0.57	0.56	0.53	0.5
THD voltage	3.5	3.7	3.7	3.8	3.7	3.8	3.7
THD current	10.7	10.7	11.3	12.8	12.7	11.0	10.9
Input voltage	121.4	121.6	121.5	121.7	121.5	121.6	121.6
Current	919.0	873.0	859.0	806.0	813.0	889.0	905.0

Lamp 11							
(°C) (Ambient temperature)	45	25	25 R	10	0	−9	−18
Time to ignite (sec)	4.0	5.5	5.0	3.5	5.0	40.0	360.0
Time to equil (min)	59.0	62.0	19.0	61.0	80.0	59.0	103.0
Temp lamp A (°C)	57.0	50.7	49.8	36.0	24.8	7.9	−2.6
Temp lamp B	58.3	48.3	49.3	36.3	31.6	17.2	5.2
Temp lamp C	62.2	47.1	46.0	32.4	31.5	13.9	1.7
Lamp luminances (cd/m^2)	17.6	13.8	18.2	18.4	14.8	9.1	4.6
Voltage (V)	0.25	0.19	0.25	0.26	0.22	0.13	0.08
LumEff (cd/m^2/W)	0.09	0.09	0.12	0.12	0.09	0.06	0.03
Relative LumEff	1.00	1.00	1.32	1.35	1.07	0.67	0.35
Power (W)	58.3	45.7	45.59	45.23	45.8	44.66	43.2
Power (V·A)	107.6	88.4	84.71	81.86	83.8	88.06	87.29
Power factor	0.54	0.52	0.54	0.55	0.55	0.51	0.49
THD voltage		3.8	3.8	3.8	3.8	3.9	
THD current		10.3	11.2	10.8	9.7	9.7	
Input voltage	122.0	122.0	121.7	122.0	121.7	121.8	121.8
Current	882.0	724.6	696.0	671.0	682.0	722.0	717.0

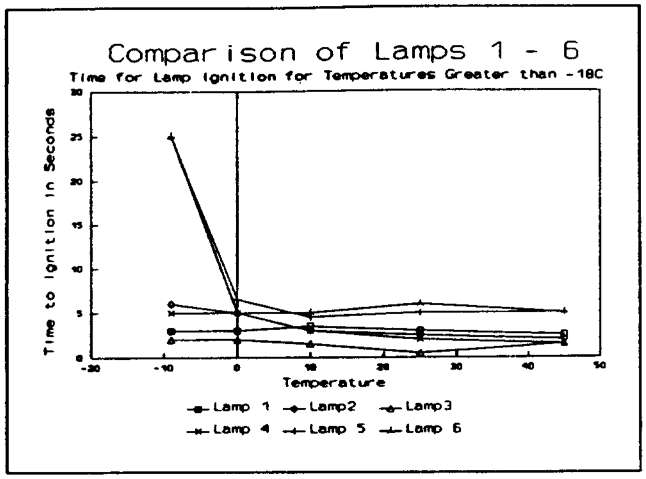
Lamp 12 (lamp voltage boosted to 13 V to get start)							
(°C) (Ambient temperature)	45	25	25 R	10	0	−9	−18
Time to ignite (s)		5.0	5.0	5.0	5.0	failed	
Lamp luminances (cd/m^2)		10.6		6.5	3.5		

Lamp 13							
(°C) (Ambient temperature)	45	25	25 R	10	0	−9	−18
Time to ignite (s)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Time to equil (min)	15.0	20.0	19.0	16.0	15.0	15.0	15.0
Temp lamp A (°C)	66.4	56.9	52.7	38.2	27.6	17.8	10.7
Temp lamp B	66.7	55.0	57.8	41.2	34.6	23.5	14.1
Temp lamp C	67.7	58.1	53.4	38.0	33.0	17.4	14.7
Lamp luminances (cd/m^2)	12.7	13.6	13.6	12.6	12.6	13.7	13.5
Lamp Output (V)	0.18	0.19	0.19	0.19	0.19	0.20	0.20
LumEff (cd/m^2/W)	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Relative LumEff	0.94	1.00	1.01	0.93	0.93	1.02	1.00
Power (W)	164.7	166.3	164.8	164.9	165.0	164.6	165.1
Power (V·A)	165.1	166.4	164.9	165.0	163.1	164.7	165.0
Power factor	1.0	1.0	1.0	1.0	1.0	1.0	1.0
THD voltage	3.9		3.9	3.9	3.9	3.9	3.9
THD current	3.9		3.9	4.0	3.9	4.0	4.0
Input voltage	121.6	122.9	121.9	121.9	121.8	121.8	122.0
Current	1353.0	1374.0	1353.0	1354.0	1354.0	1353.0	1354.0

the end of the test period. Before that, light output values for the four warmest temperatures were comparable, with only the data for 0 °C declining slightly over time. Inspection of the data suggests that the light output peaked early and then declined over time, but never really reached equilibrium at −9 and −18 °C. As to be expected there was relatively little effect of temperature on time to equilibrium or light output for the incandescent lamp, lamp 13. Comparable data were not available for the low voltage lamp, lamp 12, which had numerous electrical problems during the data collection and failed to ignite at temperatures below 0 °C.

Examination of the data for the twelve sets of compact fluorescent lamps demonstrates that most were markedly affected by temperature extremes, displaying noticeable reductions in light output at the colder temperatures with frequent reductions to 10–20 percent or less of their output at the baseline 25 °C temperature. In addition, lamps 1, 3, 5 (and 6), 7, 8, 9, 10 and 11 showed great variability in time to equilibrium. Light output and time to equilibrium were reduced for lamp 1 at 10 °C, while lamps 5, 9, and 10 displayed reduced output at 45 °C. Addition of extra humidity, by using a fine mist at −4 °C caused lamps 4, 5, and 8 to fail to ignite. Of course, lamp 8 failed outright at −9 °C. Only lamps 2 and 4, which had external globes, were relatively unaffected by the colder temperature extremes. Light output for these two lamps was reduced at the two warmer temperatures (25 and 45 °C), however. Lamp 4 contained an integral electronic ballast, as did lamp 3 which demonstrated much greater temperature sensitivity than lamp 4. These data suggest that presence of an enclosure, or globe, improved performance at colder temperatures as indicated by the results for lamps 2 and 4. Even the poor performance of lamp 5 at low temperatures was improved by the addition of an enclosure, as can be seen from the data for lamp 6. In contrast, the presence of a globe appeared to reduce light output at the warmest temperatures. Nonetheless, temperature extremes, both low and high, reduced overall light output and increased the time to luminous equilibrium for almost all the compact fluorescent lamps studied.

Because of the difficulty of comparing performance for different lamps from **Table 2**, some of the key data are summarized graphically. In the following figures the upper plot refers to lamps 1 through 6, while the lower plot presents data for lamps 7 through 13. **Figure 1** which presents time to ignition as a function of ambient temperature for temperatures greater than −18 °C makes it very clear that time to ignition was greatly affected by temperatures below 0 °C, particularly lamps 5, 6, 7, 10 and 11 (as well as 8 which



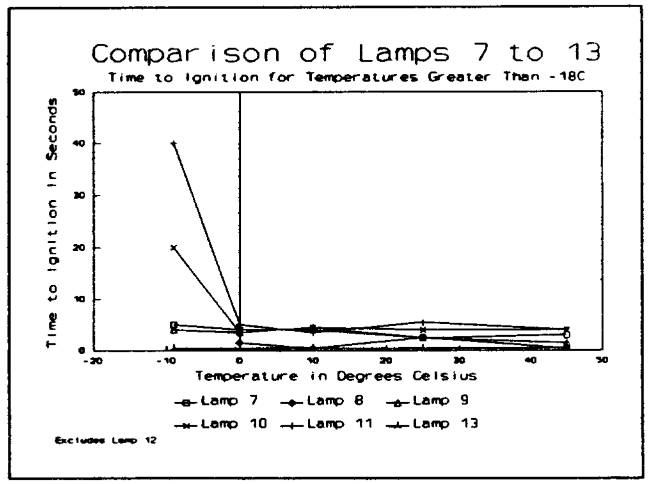


Figure 1—Ignition time for all lamps at ambient temperatures above −18 °C

failed completely at these temperatures.) For these lamps, ignition time increased from less than 5 s to 40 or more s. At −18 °C, the time to ignition increased to 400 to 500 s for lamps 5, 6, 7, 10, and 11. At the same time, ignition time for the incandescent lamp, 13, remained at less than 0.5 s, regardless of changes in ambient temperature.

Figure 2 summarizes the data presented above on time to equilibrium as a function of ambient temperature. While there may be a trend toward increasing time with decreasing temperature, these two plots demonstrate a great deal of variability in the general trends. **Table 2**, which indicates the time to equilibrium for lamps 2, 4, 8, and 10 between the first test at 25 °C and the second, suggests that they may not have been fully burned in at the beginning of the experiment. **Figure 3** plots the lamp outer wall (tip) temperature (for the warmest of the three lamps) as a function of ambient temperature. These two graphs make it very clear that lamp tip temperature declined markedly as ambient temperature decreased which probably explains the drop in performance that oc-

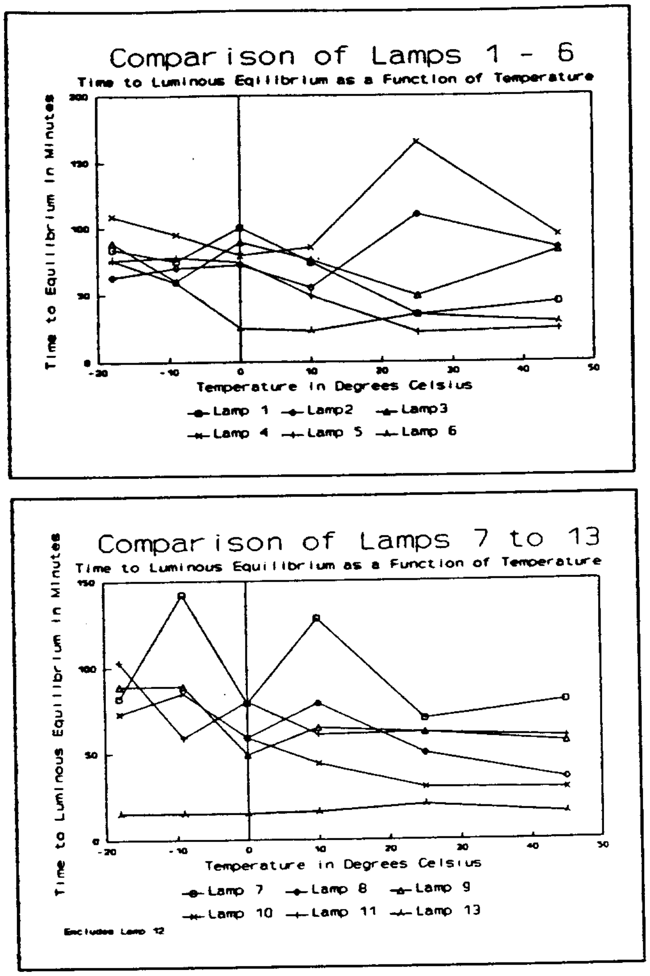


Figure 2—Time to luminous equilibrium at different ambient temperatures.

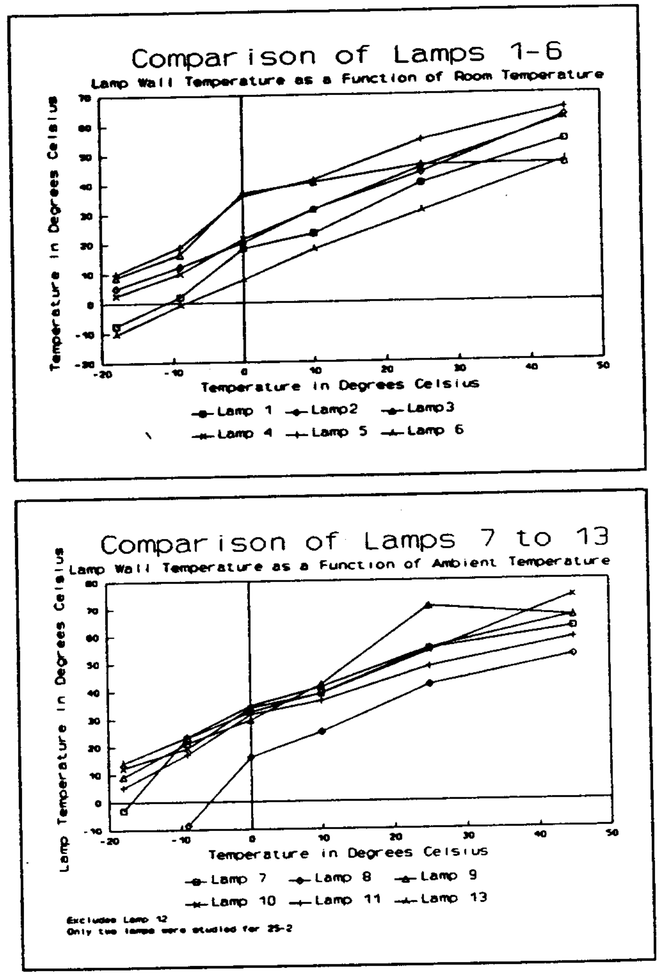


Figure 3—Lamp outer wall temperature at different ambient temperatures.

curred with lower temperatures. By 10 °C lamp tip temperature for lamps 1, 6, and 7 was below 30 °C which is below the temperature for which optimum performance is expected for fluorescent lamps (IESNA, 1984). By −9 °C, all lamps had lamp tip temperatures below this temperature. Lamp tip temperature was something of a misnomer for lamps 2, 4, and 6 which were comprised of a globe around the lamp itself. Comparison of the temperatures for lamps 5 and 6 in **Figure 15** demonstrate the likely thermal effects of the globe with lamp 5 having the warmest and lamp 6 having the coolest temperatures. Lamp apparent power in volt amps as a function of temperature tended to remain relatively stable over temperature for most lamps. Some lamps, such as 2, 4, 10, 11, and 13, displayed almost no variation in volt amps across temperatures. The ones with the greatest variation were 1, 3, 5, 6, 7 and 8. The latter two varied of course, because of the loss of one or more lamps at cold temperatures. Input current for the different ambient temperatures tended to decrease for lamps 1 and 4, but remain relatively constant for the other lamps (except 5, 6, and 8 which experienced ignition problems at temperatures below −9 °C). The power factor generally was around 0.55 with some variations due to temperature (primarily for lamp 1). Power factor did not vary much for different temperatures (except lamp 8 which was close to failure at −9 °C), and was generally about 0.55 for all lamps except 3, 8, and of course 13 which was at 1 as expected. Only lamp 8 of the compact fluorescents had a power factor near 1, which dropped dramatically for −9 °C to about 0.25. (This lamp contained a high power factor correction circuit as well as a constant illumination circuit.) The data for harmonic distortion, for both current and voltage, demonstrate little variation in these parameters as a function of temperature for the performance of the different lamps. Lamps 3 and 4 had higher total harmonic distortions for both current and voltage regardless of temperature.

Figure 4 presents data on lamp light output as measured by the photocell for the different ambient temperatures. Although they are not plotted, the measured luminance data are virtually identical with the photocell output (even though the measurements were obtained with different procedures and instruments). **Figure 4** shows a generally declining output with decreasing temperature.

Lamps 1, 3, 6, 7, and 9 demonstrated a sharp decrease in luminance and photocell output with temperature, with lamps 1 and 7 showing a decrease by 10 °C. The decline in output was much less pronounced for lamps 2, 4 and, of course, 13. The repeated measures at 25 °C demonstrated relatively little change from the initial measures. Lamp apparent power in volt amps as a function of temperature tended to remain relatively stable over temperature for most lamps. Some lamps such as 2, 4, 10, 11, and 13 displayed almost no variation in volt amps across temperatures. The ones with the greatest variation were 1, 3, 5, 6, 7 and 8. The latter two varied, of course, because of the loss of one or more lamps at cold temperatures. Input current for the different ambient temperatures tended to decrease for lamps 1 and 4, but remain relatively constant for the other lamps (except 5, 6, and 8 which experienced ignition problems at temperatures below −9 °C). The power factor generally was around 0.55 with some variations due to temperature (primarily for lamp 1). Power factor did not vary much for different temperatures (except lamp 8 which was close to failure at −9 °C), and was generally about 0.55 for all lamps except 3, 8, and of course 13 which was at 1 as expected. Only lamp 8 of the compact fluorescents had a power factor near 1, which dropped dramatically for −9 °C to about 0.25. (This lamp contained a high power factor correction circuit as well as a constant illumination circuit.) The data for harmonic distortion, for both current and voltage, demonstrate little variation in these parameters as a function of temperature for the performance of the different lamps. Lamps 3 and 4 had higher total harmonic distortion for both current and voltage regardless of temperature.

While the primary means for monitoring the light output of the lamps was a silicon photocell located within the environmental chamber, a supplemental procedure for measuring light output was developed to account for any thermal instabilities of the photocell. In this procedure, the luminance of a white tile located below the lamps was measured to evaluate whether the photocell response changed with ambient temperature. For these measures, a luminance meter which was kept outside the environmental chamber, was brought into the chamber very briefly to measure the luminance of the white tile. Because the luminance of the tile is proportional to lamp light output, and independent of ambient temperature, it could verify the thermal stability of the photocell and provide further data on the light output of the lamps for a standard condition, although it did not, of course, provide absolute luminance data. Comparison of the photocell and luminance meter measures indicated insignificant temperature dependence for the photocell under the range of testing conditions, with differences for individual lamps ranging from 0.009 to 0.18. The average difference between meter readings for all lamps for all temperatures was 0.014 with a standard deviation of 0.001. There was good agreement between the two types of measures with the best agreement occurring at 10 and 25 °C. This analysis thus indicates that the photocell remained sufficiently stable over temperature that comparisons between the performance of different lamps at different temperatures can be made.

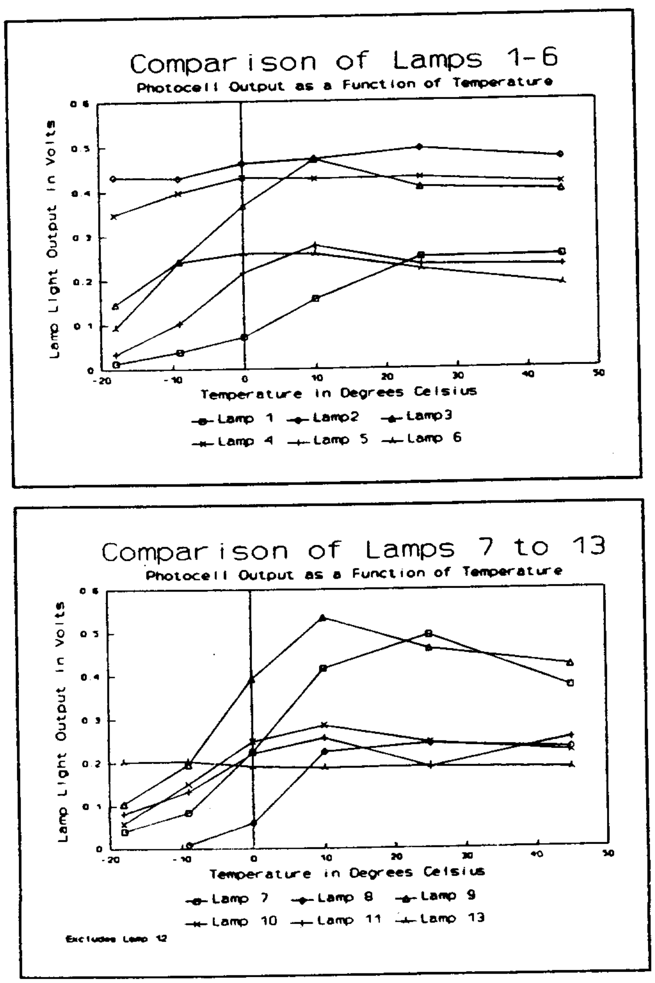


Figure 4—Measured light output at different ambient temperatures.

Figures 5 and **6** plot the data for the lamps normalized to their individual maximums for ready comparison of lamp performance on a single plot. Lamps may also be compared relative to performance at a reference temperature such as 25 °C.[3] **Figure 5** plots input power in watts as a function of temperature for the different lamps. As can be seen, input wattage generally remained relatively constant with marked decreases only for lamp 3 at 45 °C, and for lamps 7 and 8 at −9 and −18 °C (because one or more lamps failed at the low temperatures). Inspection of the data in **Table 2** indicates that the incandescent lamp, 13, required the greatest power although lamps 7, 8 and 9 (being 24 W or more) required more power than the other lamps.

While total lamp lumen output was not measured directly, the photocell data provide a measure of relative luminous output. Consequently, a form of lamp efficacy could be calculated for each set of lamps at different thermal conditions. This comparison was termed relative luminous efficacy and is only an approximation because the lamps differed in size and distance from the photocell. As a result the photocell could not measure the total luminous distribution.

Figure 6 presents a comparison of relative luminous efficacy normalized to the same lamp's maximum performance at any temperature. Examination of **Figure 6** makes it very clear that the relative luminous efficacy for the incandescent lamp, 13, remained relatively constant as temperature varied. All the compact fluorescent lamps, however, showed reduced output at the colder temperatures, with markedly reduced output at −18 °C. Only lamps 2 and 4 appeared to be somewhat unaffected by temperature with relative luminous efficacies greater than 0.8 throughout the experiment. Lamps 1 and 8, on the other hand showed markedly reduced efficacy even at 10 °C with a pronounced decline for lower temperatures. Comparison of lamps 5 and 6 reveals that when the globe was used, relative luminous efficacy increased, but when it was not used efficacy dropped dramatically at 0° and −9 °C. This is likely due to heating of the lamp when enclosed by the globe. Efficacy declined markedly for both configurations at −18 °C, however. Inspection of the lower plot reveals that lamps 9, 10, and 11 actually increased their efficacy at 10 °C, while 7 and 8 began to decline. (Relative efficacy for these two lamps was, of course, markedly affected by the failure of one or more lamps below 10 °C.) Despite the decreases in relative luminous efficacy, for most of the temperature tests, relative luminous efficacy remained greater for the compact fluorescent lamps compared with that of the incandescent. For temperatures above −9 °C, relative luminous efficacy was much greater for the compact fluorescents, despite their declining output at colder temperatures. By 0 °C, only two lamps, 1 and 8, had efficacies below that of the incandescent lamp. By −18 °C, the efficacy for lamps 1, 5, 8 (which had totally failed), 7 (which was lacking one lamp but which had been well above lamp 13 even for 0 °C), 9 and 10 had fallen below that of lamp 13. At least two lamps, 2 and 4, maintained reasonably high relative luminous efficacies throughout all the test temperatures. Even at −18 °C their relative efficacy was six to eight times that of the incandescent lamp.

Finally, a comparison of performance for the different lamps at 25 °C taken at the beginning and end of the testing sessions for the data on time to equilibrium, light output, and relative lamp efficacy suggests that the lamps were not harmed by the thermal extremes (as we had hypothesized that they might be.) Rather the data suggest that the 100 hrs of burn time prior to the thermal testing may not have been quite long enough to age and stabilize the lamps completely—or that the procedures for data collection may have increased in stability during the course of the experiment.

Conclusions and recommendations

The most important conclusion to be reached from these data is that temperature variations from the normal temperature of 25 °C greatly reduced lamp light

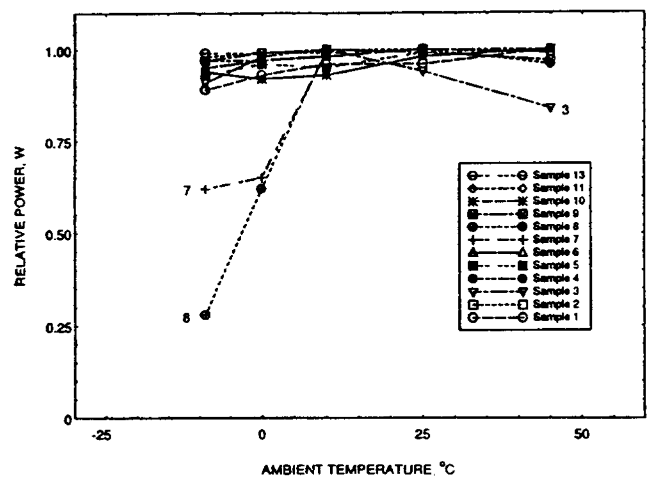


Figure 5—Effect of temperature on power consumed by compact fluorescent systems.

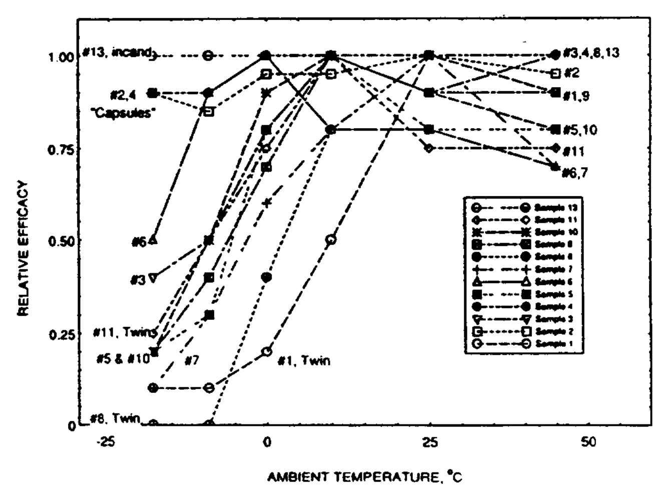


Figure 6—Effect of temperature on relative efficacy of compact fluorescent systems.

output and increased the time to luminous equilibrium. Lamps that were markedly affected by temperature displayed noticeable reductions in light output—sometimes being reduced to 10–20 percent or less of their output at the baseline 25 °C temperature. Outright failure occurred in other cases. In addition, their time to equilibrium demonstrated much greater variability. This finding is in accordance with results generally found for conventional fluorescent lamp performance.[8] The only design factor that appeared to moderate this finding was the presence of an outer globe surrounding the fluorescent tube. Lamps using this configuration did not suffer the declines in light output at low temperatures experienced by the other compact fluorescents. Their light output declined for higher temperatures, however.

Despite reductions in performance due to temperature extremes, the other major conclusion is that the compact fluorescent lamps remained noticeably more efficient than the comparison incandescent lamp until very low temperatures (usually below freezing, 0 °C) were reached. These lamps consistently produced more light output for less power input, as compared with the reference incandescent lamp. This effect varied for lamp type—those with an enclosing globe tended to demonstrate less performance decrement at the lower temperatures. The low voltage system was not particularly successful, however, perhaps because of the novelty of the design which resulted in inadequate isolation of the electrical components in the test situation. As others have reported, power factor for the compact fluorescents was typically low, around 0.55, for the compact fluorescent designs studied, while harmonic distortion was noticeably higher for three of the lamps studied. Flicker index was in line with reported data for other types of fluorescent lamps.[5]

The data suggest that the selection of a particular compact fluorescent system should be based on its likely application. If the space is likely to be cold, then a lamp with an integral enclosure (or globe) should be selected for maximum light output. If it is likely to be hot (above 25 °C) then such an enclosure is likely to overheat the lamp, resulting in lower light output. Still another factor for design consideration is the marked variation in size of the different lamps and ballasts. In addition, for some of the lamps the ballast was an integral component of the fixtures, whereas for others, such as lamps 7, 8, and 9, the ballast was separate and required wiring before use. Finally, the compact fluorescents studied here tended to decrease in light output over the time of operation at extreme temperatures, particularly when stressed by temperature, another factor which may be of concern in some applications.

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Discussion

The light output of a fluorescent lamp is greatly affected by the mercury pressure. The mercury pressure can be controlled by a cold spot on the lamp. Another possibility of mercury pressure control is by an amalgam in the lamp. The major benefit of an amalgam is the large temperature range over which the mercury pressure, and consequently the light output of the lamp, is kept almost constant. Lamps 2 and 4 in your test have a light output that is almost independent of the ambient temperature. Is it possible that this temperature independence is largely caused by the use of an amalgam and to a lesser extent to the pressure of an outer globe?

P.M. den Breeijen
Philips Lighting Company

The authors conclude that lamps which have a cover surrounding the discharge tube do not exhibit reduced light output at low ambient temperatures. Can the authors conclusively state that the cover produces this effect, or could it be due to an amalgam in the lamp which controls the mercury vapor pressure over a wide ambient temperature range?

A. Serres and J. Schlejen
Philips Lighting Company

Authors' response

To P.M. den Breeijen, A. Serres, and J. Schlejen

The discussors raise the issue of the possible presence of an amalgam in lamps 2 and 4. Subsequent checking revealed that these two lamps did, in fact, have an amalgam. As the discussors point out, this may have been responsible for some of the temperature effects. Comparison of the performance of lamp 5 with lamp 6 (which consisted merely of adding a globe to lamp 5) also substantiates the idea that the globe played an important role in shielding the lamp from the cold temperature. It is likely that the two factors contribute to lamp performance under cold temperatures. Further research should be conducted to separate the effects of amalgam from thermal shielding on the performance of compact fluorescent lamps.